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Spatiotemporal Distribution Characteristics of Actual Evapotranspiration in the Qinghai–Tibet Plateau

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Abstract: Evapotranspiration is a key part of the water cycle between the atmosphere and the land surface, and it is an important parameter for studying the land–atmosphere system. Change and evolution have important implications. Therefore, the understanding and research of actual evapotranspiration (AET) can profoundly affect water use, ecological environment, temperature, and precipitation. In this paper, the single-layer monthly average reanalysis meteorological data of the Qinghai–Tibet Plateau from 1981 to 2020 was used to study and calculate the actual evapotranspiration in the Qinghai–Tibet Plateau, and the temporal and spatial variation characteristics, variation laws, and changes were analyzed by methods such as cumulative anomalies and the Mann–Kendall trend test. The results showed the following: (1) The evapotranspiration gradually decreased from southeast to northwest. The evapotranspiration in the southeastern region is strong, and the maximum value appears in the Hengduan Mountains. (2) The evapotranspiration was the largest in summer and gradually decreased from southeast to northwest; the evapotranspiration in spring and autumn was relatively uniform, with little overall difference, and the evapotranspiration was the lowest in winter. (3) There were mainly three spatial distribution modes of evapotranspiration in the Qinghai–Tibet Plateau, which were characterized by a significant and consistent change centered on the Tibet region, an east–west reverse type, and an east–west "negative-positive-negative" of the distributed three-pole space. The corresponding time coefficients characterized the interdecadal and interannual variation, and the decadal variation characteristics are more significant than the annual variation characteristics. (4) The actual evapotranspiration had step change; the step change years were 1989, 2002, 2011, and 2015, and there was an interval of about 5 years.

Keywords: Qinghai-Tibet Plateau; actual evapotranspiration; spatiotemporal distribution; Mann-Kendall trend test

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1. Introduction

The Qinghai–Tibet Plateau, located in the interior of Asia, is the largest plateau in China and the highest plateau in the world. It is called "the roof of the world" and "the third pole" [1]. The Qinghai–Tibet Plateau ranges from the Himalayas in the south to the Kunlun Mountains, Altun Mountains, and the northern edge of the Qilian Mountains in the north, and from the Pamir Plateau and Karakoram Mountains in the west to the Hengduan Mountains in the east, connecting with the western section of the Qinling Mountains and the Loess Plateau, with a total area of about 2.5 million square meters. It is the plateau with the highest average altitude, the largest area, and the most complex terrain in the world [2,3].

The energy and water on the surface of the plateau are characterized by large and rapidly changing exchange rates with the atmosphere. The underlying surface is the main source of heat and water vapor in the atmosphere. It is located in the middle of the troposphere. The thermodynamic action of the atmospheric circulation becomes uplifting and heating [4], and this thermodynamic action plays a very important role in the Asian climate system. Therefore, it is of great significance to study the land–atmosphere interaction of the Qinghai–Tibet Plateau. This land–atmosphere interaction had a profound impact on the climatic conditions of the Qinghai–Tibet Plateau and its surrounding areas.

The average elevation of the Qinghai–Tibet region is over 4000 m, and many peaks are perpetual snow and ice. Glaciers are widely distributed, and snow-capped mountains are continuous. The natural environment is mainly characterized by high and cold temperatures. Therefore, the water resources of the Qinghai–Tibet Plateau exist in various forms of water bodies, such as rivers, lakes, glaciers, and groundwater, with river runoff as the main body. The southeastern region is rich in precipitation, and the river supply in the inland region mainly relies on the melting of glaciers or snow, hence it is known as the “Asian Water Tower” [5]. At present, with global warming, the precipitation on the Qinghai–Tibet Plateau has shown an overall increasing trend in recent decades [6]. At the same time, the changes in lakes and vegetation have also undergone significant changes in the late 1990s [7]. Therefore, the original land air balance will also be disrupted, resulting in changes in the distribution of glaciers, lake evolution, and the ecological environment of the plateau itself. Therefore, further in-depth research on the changes in actual evapotranspiration in the Qinghai–Tibet Plateau region is particularly important. This not only has important value for water resource security and ecological environment protection in China but also plays an important role in the research process of hydrological changes in surrounding areas.

Actual evapotranspiration (AET) is the sum of soil evaporation, water surface evaporation, and vegetation transpiration under different climates and underlying surface conditions [8]. Direct participation in the hydrological cycle is an important part of the water cycle process and surface energy balance [9]. Terrain, climate, and underlying surface all have an impact on AET, and AET is also an important parameter affecting the ecological process of the land surface [10], but the current research on evapotranspiration mainly focuses on the arid and semi-arid regions in the north [11], and there is a lack of research on the correlation characteristics of actual evapotranspiration in the Qinghai–Tibet Plateau. Therefore, it is of great significance to deeply understand the actual surface evapotranspiration and the process of material circulation and energy conversion in the atmosphere, study its impact on the Qinghai–Tibet Plateau, establish a reasonable land surface process model, and improve and study the climate model.

The innovation of this study is that it effectively supplements the research on the relevant characteristics of actual evapotranspiration in the Qinghai–Tibet Plateau region, and its research results provide a further understanding of the spatiotemporal changes in evapotranspiration in the Qinghai–Tibet Plateau region in recent years. This not only deepens the understanding of the land–atmosphere interaction in the Qinghai–Tibet Plateau region, but also facilitates the study of future changes in weather, climate, hydrology, and ecology in the region. It is also of great significance for the study of water cycles under the influence of climate change and vegetation structure changes.

2. Materials and Methods

2.1. Data Sources

The data used are as follows: ERA5 reanalysis data from the European Forecast Centre (https://cds.climate.copernicus.eu) (accessed on 5 August 2022) for the period 1981–2020. The time resolution is 1 h, and the horizontal resolution is $0.25^\circ \times 0.25^\circ$. The latitude and longitude range is 25–45° N, 70–120° E, including Xinjiang, Tibet, Gansu, Qinghai, Sichuan, and other provinces and cities (Figure 1).

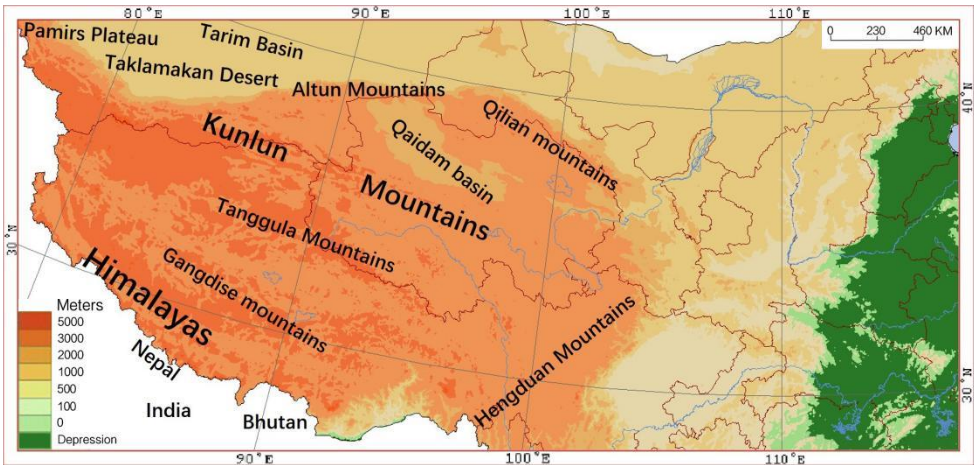

Figure 1. The schematic map of the study area.

2.2. Methods

The empirical orthogonal function analysis method (EOF), also known as the eigenvector analysis method, takes the time series of the field as the analysis object and considers the significance of maximum variance by choosing the order of the eigenvectors associated with the largest eigenvalues of the covariance matrix. It is the same as performing a principal component analysis on the data, except that the EOF method can find temporal and spatial patterns.

It divides the time-varying variable field into a time-invariant spatial function and a time-dependent time function, namely, the principal component part [12]. The variance contribution rate of the first few fields of the principal component is relatively large, which is convenient for processing and studying a large amount of data [13]. By using the EOF method to analyze evapotranspiration in the Qinghai–Tibet Plateau, we can understand the spatial distribution and temporal variation characteristics of evapotranspiration in the region over the past 40 years.

The power spectrum of the periodic variation of the variable can be analyzed in detail, the variation law of the complex signal can be further understood, and the time series of the principal component of the EOF calculation can be progressively analyzed. Spectral analysis functions and confidence interval calculation functions can better capture the periodicity of time series [14].

The Mann–Kendall step change test can determine the significance of the trend by calculating the trend of the sequence. It can also be used to detect step changes in time series, returning the time when the step change occurred. The nonparametric test method, also known as the arbitrary distribution test, or Mann–Kendall test, does not require samples to follow a certain distribution, and a small number of outliers will not interfere with it. At the same time, it does not make strict assumptions about the distribution of variables, nor does it check specific parameters. Instead, it vaguely examines the center position and distribution state of the variable's distribution. Because it makes no strict assumptions about the overall distribution, it has strong applicability. It is widely used in the field of hydrometeorology [15,16].

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3. Results and Discussion

3.1. Climate Averages

3.1.1. Spatial Distribution

Figure 2 shows the spatial distribution of evapotranspiration in the Qinghai–Tibet Plateau from 1981 to 2020. It can be seen that the evapotranspiration gradually decreases from southeast to northwest. The evapotranspiration in the southeast is strong, and the maximum value appears in the Hengduan Mountains, and the maximum value can reach 2.2 mm–m^{-2}. The Qaidam Basin, located in the northern part of the Qinghai–Tibet Plateau, has less evapotranspiration because evapotranspiration is the main mode of water balance in the inland basins in the arid region [17], which is consistent with the topographic features of the Qaidam Basin and the Gobi.

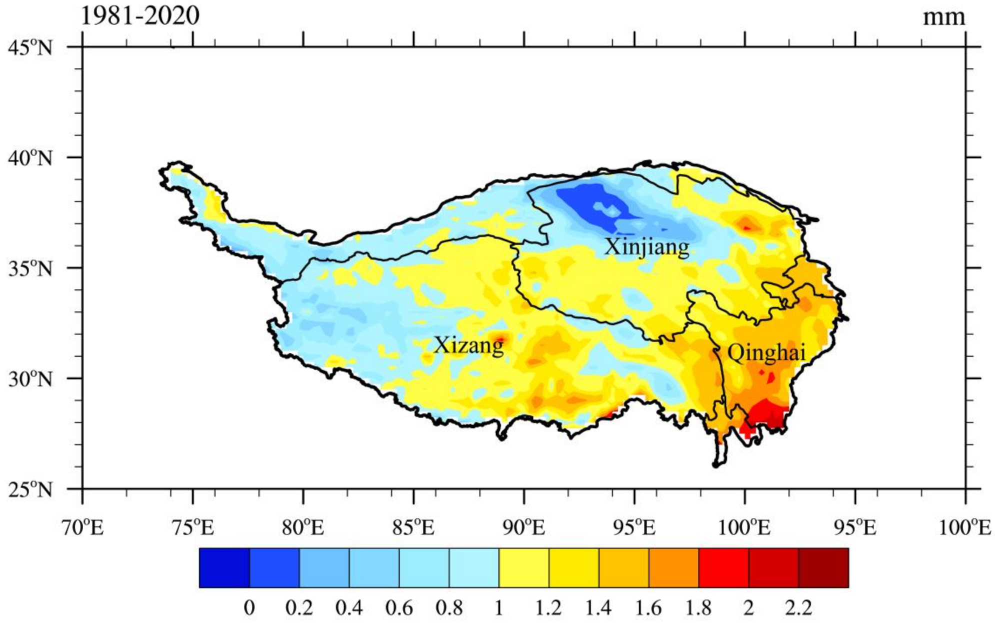

Figure 2. The spatial distribution of the average annual actual evapotranspiration over the Tibetan Plateau during 1981–2020 (unit: mm of depth of AET).

The evapotranspiration value can also accurately reflect the amount of vegetation and the storage degree of precipitation. At present, NDVI is widely used for vegetation growth changes and its interaction with the climate. It expresses vegetation information through infrared and near-infrared bands to understand vegetation growth status and vegetation coverage [18,19]. Zhou et al. [20] used the plateau NDVI data to study the evolution characteristics of plateau vegetation and its influencing factors. The results showed that the temporal and spatial distribution and changes of plateau vegetation showed that the vegetation coverage in the southeast of the plateau was the best, and the vegetation coverage in the northwest gradually deteriorated. This is consistent with the characteristic that the overall mean evapotranspiration showed a gradual decrease from southeast to northwest. At the same time, it also corresponded to the unique distribution of water and heat conditions in the Qinghai–Tibet Plateau, which is warm and humid in the southeast and cold and arid in the northwest [21].

The special and complex topography of the Qinghai–Tibet Plateau makes the spatial variation of evapotranspiration quite different. Wang et al. [22] used the soil temperature prediction correction method (TDEC) to compare and analyze the surface energy flux and evapotranspiration. The results showed that the seasonal variation of evapotranspiration is significant, with the strongest being in summer, the second in spring and autumn, and the smallest in winter. Zhang et al. [23] used the precipitation and evaporation data from the atmospheric reanalysis data to study the changes in water sources in the Qinghai–Tibet Plateau using an improved water accounting model. The results show that there are significant differences in the contribution areas of water vapor sources in the southern and northern parts of the Qinghai–Tibet Plateau. The water vapor source area is divided into the Qinghai–Tibet Plateau, the northwest source area, and the southeast source area. The northwest source area is controlled by the westerly wind system, and the southeast source area is controlled by the monsoon system. The water vapor contribution of the northern Qinghai–Tibet Plateau mainly comes from the northwest source area and the Qinghai–Tibet Plateau, of which the northwest source area contributes 39–43%, the Qinghai–Tibet Plateau contributes 26–30%, and the water vapor contribution of the southern Qinghai–Tibet Plateau mainly comes from the southeast source in the region, whose contribution was 51–54%, and the contribution of the Qinghai–Tibet Plateau accounted for 14–16%. The water vapor brings good precipitation conditions and increases local evapotranspiration. The research of Tang et al. [24] showed that in recent years the water vapor contributed by the northwest source area controlled by the westerly wind belt west of the Qinghai–Tibet Plateau has decreased significantly. Showing an increasing trend, the above-mentioned changes in the contribution of water vapor source regions have led to differences in precipitation trends in the Qinghai–Tibet Plateau and its surrounding regions.

Due to the influence of precipitation differences brought about by complex terrain and water vapor transport, the spatial distribution of evapotranspiration in the Qinghai–Tibet Plateau in the different seasons of spring, summer, autumn, and winter from 1981 to 2020 was also generally different (Figure 3). It can be seen that the contribution of evapotranspiration is the largest in summer, the coverage in the east and south is the best, and the coverage in the west and north decreases; the contribution of evapotranspiration in spring and autumn is equal, and the overall difference is not large, but the evapotranspiration in the southeast is relatively higher; evapotranspiration is least in winter. This corresponds to the precipitation, vegetation coverage, and obvious climatic characteristics of the Qinghai–Tibet Plateau, but on the whole, the evapotranspiration in the southeast of the Qinghai–Tibet Plateau has been at a high value throughout the year, while the annual evapotranspiration of the Qaidam Basin in the northern part of the Qinghai–Tibet Plateau is relatively low.

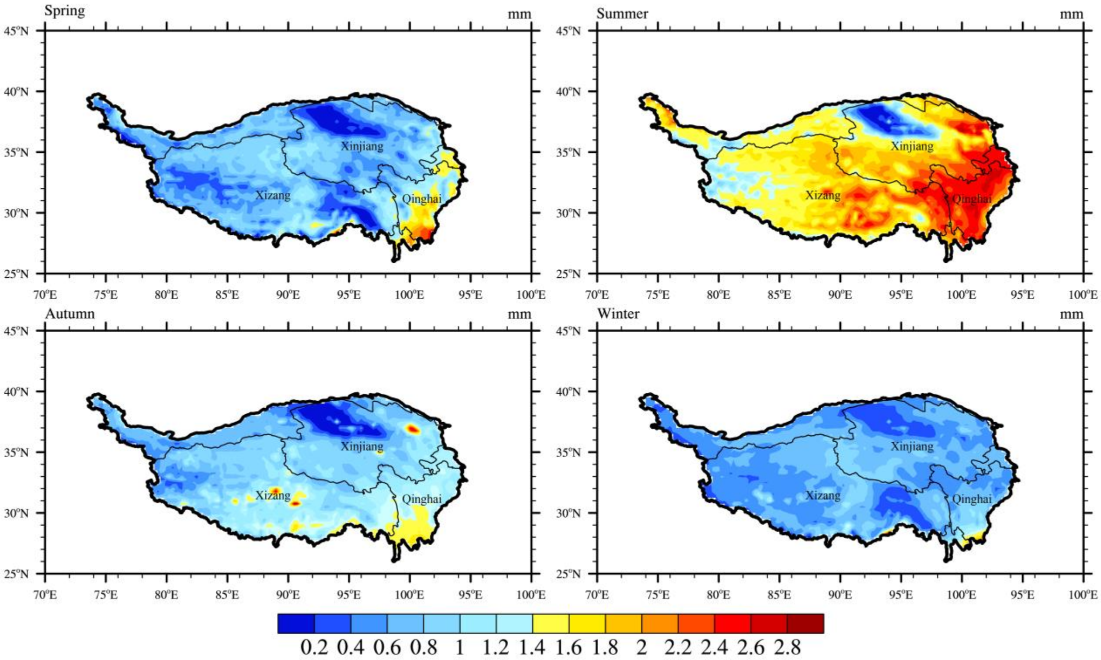

Figure 3. The spatial distribution of the average evapotranspiration over the Tibetan Plateau in spring, summer, autumn, and winter during 1981–2020 (unit: mm of depth of AET).

3.1.2. Annual Variation

Yin et al. [21] used the improved LPJ global vegetation dynamic model (Lund–Potsdam–Jena Dynamic Global Vegetation Model) to simulate the temporal and spatial changes of actual evapotranspiration caused by climate change in the Qinghai–Tibet Plateau in the past 30 years. The results show that with the background of global warming as the main feature, the actual evapotranspiration in most areas of the Qinghai–Tibet Plateau shows an increasing trend.

From the interannual variation of evapotranspiration anomalies and their trends in the Qinghai–Tibet Plateau from 1981 to 2020 (Figure 4), it can be seen that most years before 1995 were negative anomalies, especially from 1982 to 1993. After 1998, it turned into a persistent positive anomaly, then it began to decrease significantly from 2009, and a negative anomaly appeared in 2012. After 2016, the anomaly increased to a positive value, and it weakened again after 2018. There is a gradual strengthening process of oscillation. The possible reason is that under the background of global warming, the region has relatively sufficient precipitation, the potential evapotranspiration has increased relatively, the atmospheric water demand capacity has been enhanced, and the land water conservation capacity has increased, resulting in a gradual oscillating increase in actual evapotranspiration.

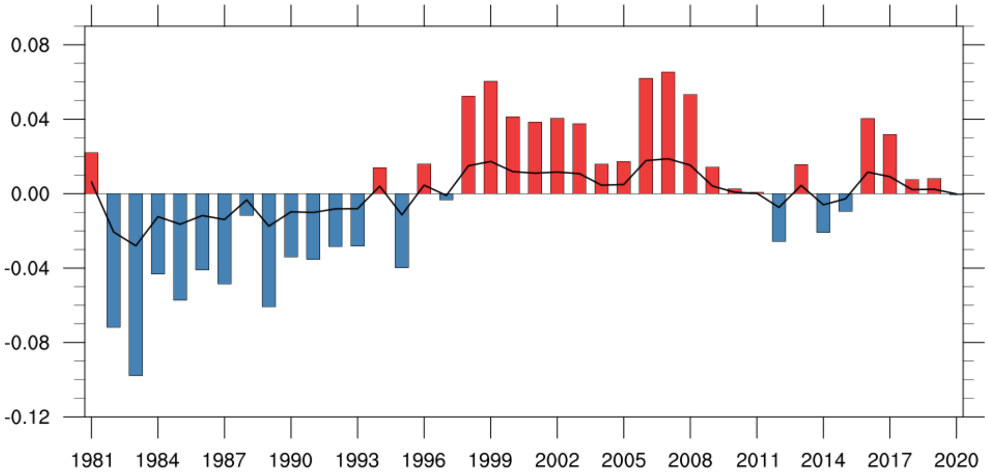

Figure 4. Interannual variations of the average evapotranspiration over the Tibetan Plateau and their climate trends during 1981–2020 (unit: mm of depth of AET).

3.2. Qinghai–Tibet Plateau Evapotranspiration Based on EOF Analysis

3.2.1. Time and Space Changes

Most of the Qinghai–Tibet Plateau is arid and semi-arid regions, the northern region is dominated by arid regions, and the central and southern regions are sub-humid and humid regions. Affected by precipitation, temperature, vegetation cover, southwest Indian monsoon, mid-latitude westerly wind, etc., the actual evapotranspiration has a significant difference, and the climate parameters also have obvious seasonal changes [25].

Figure 5 shows the main spatial modes of evapotranspiration from the Qinghai–Tibet Plateau from 1981 to 2020 obtained by EOF decomposition. The cumulative variance contribution rate of the first three modes of EOF decomposition reached 51.2% and passed the North 95% significance test (North et al. 1982) [26], indicating that the first three modes are physically meaningful signals and are statistically distinguishable. Therefore, Figure 5 shows the first three modal space types and standardized time coefficients of evapotranspiration EOF decomposition in the Qinghai–Tibet Plateau from 1981 to 2020. It can be seen that the variance contribution rate of the first mode is 31%, and the spatial pattern shows a significant and consistent change centered in the Tibet region, and the center of positive values is located in central Tibet. The corresponding time coefficients have obvious characteristics, and most of them were positive before 1995, indicating that the evapotranspiration in the Qinghai–Tibet Plateau was generally larger before 1995; however, after 1995, the time coefficients changed from positive values to negative values. It can be seen that the trend of the space changed. The increase and decrease of the change have obvious interdecadal variation characteristics of about 15 years. The evapotranspiration in the southwest region changed from strong to weak and from positive to negative.

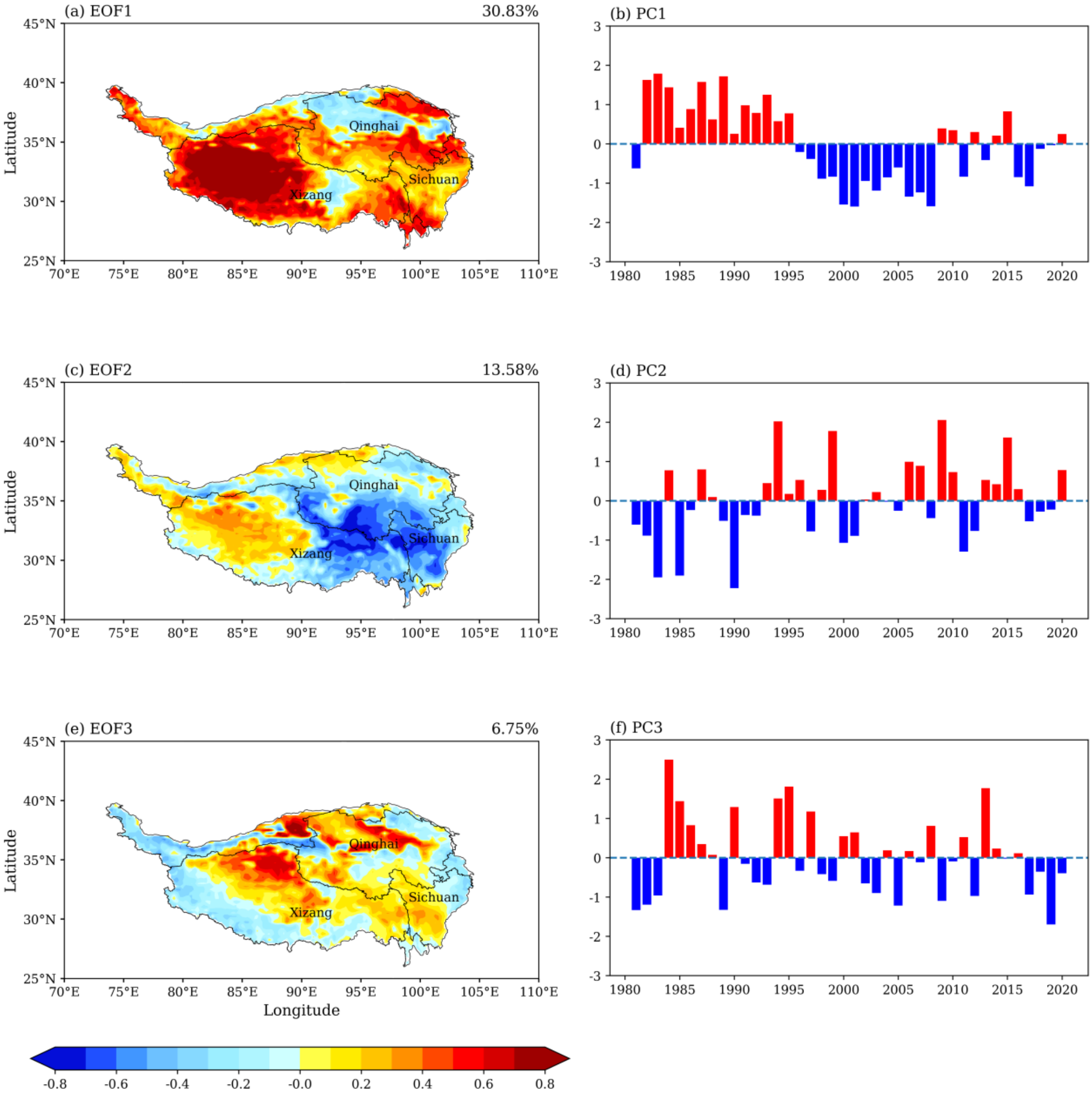

Figure 5. Spatial patterns (left panes) and standardized time coefficients (right panes) of the first three modes of the EOF analysis of the average evapotranspiration over the Tibetan Plateau during 1981–2020.

The variance contribution rate of the second mode is 13.58%, and the spatial pattern changes in an east–west reverse direction. The positive center of the western region is located in the central region of Tibet, and the negative center of the eastern region is located at the intersection of Qinghai, Sichuan, and Tibet. When the time coefficient is positive, it indicates that the value of evapotranspiration changes from negative in the west to positive in the east, and the centers of positive and negative value changes are located in the southwest corner and the southeast corner, respectively. In addition, the time coefficient also shows that evapotranspiration has obvious interannual variation characteristics of 3~5a, and the interannual variation is significant. The variance contribution rate of the third mode is 6.75%, and its spatial pattern is an east–west “negative-positive-negative” three-pole distribution, and Qinghai has a strong evapotranspiration center. The positive and negative phases of the time coefficient fluctuate frequently and cross obviously, but the positive phase changes slightly more than the negative phase, indicating that the evapotranspiration from the Qinghai–Tibet Plateau increased slightly in the fluctuations during the 40 years from 1980 to 2020.

To sum up, there are three spatial modal distributions of evapotranspiration in the Qinghai–Tibet Plateau. The first mode represents the significant and consistent variation characteristics of evapotranspiration in the Qinghai–Tibet Plateau centered on the Tibet region; the second mode represents the evapotranspiration in the Qinghai–Tibet Plateau. The east–west reverse type of spatial modal distribution has obvious positive and negative changes; the third mode represents the three-pole spatial distribution of evapotranspiration in the east–west direction of "negative-positive-negative" in the Qinghai–Tibet Plateau, and the border area of Xinjiang, Tibet, and Qinghai has a positive value in the central area and decreases towards the east and west. In addition, the first mode shows the interdecadal variation characteristics of evapotranspiration, and the second and third modes show the interannual variation characteristics of evapotranspiration.

3.2.2. Frequency Analysis

Figure 6 shows the power spectrum analysis of the 40-year monthly data of evapotranspiration in the Qinghai–Tibet Plateau from 1981 to 2020. It can be seen that there are cycles of 3a, 5a, and 12a in the Qinghai–Tibet Plateau, that they all pass the 95% confidence level, and that the cycle of 12a is more significant. It shows that there are interannual and interdecadal variation characteristics of evapotranspiration in this area, and the interdecadal variation signal is stronger than the interannual variation signal, which corresponds to the change of the time coefficient and further verifies the interdecadal variation characteristics of the actual evapotranspiration.

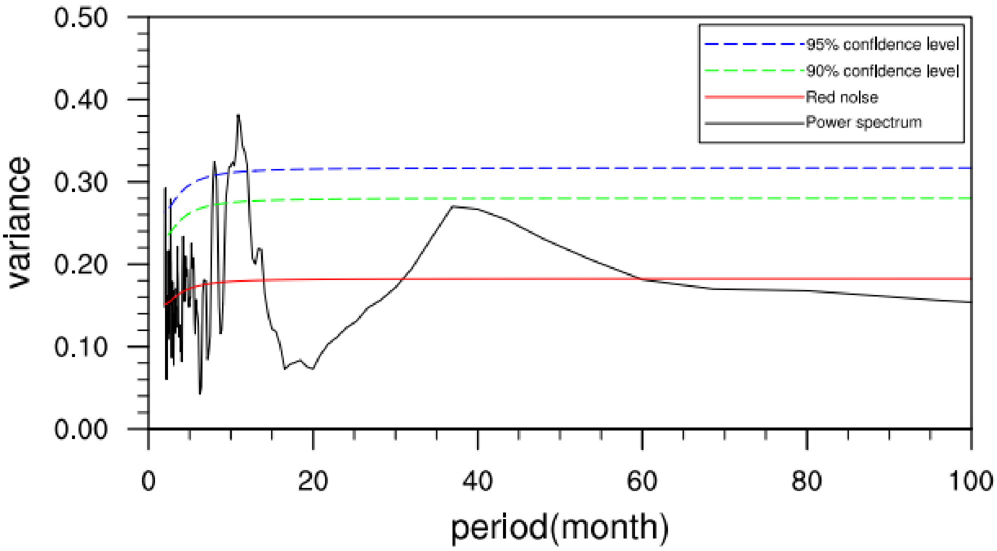

Figure 6. Power spectrum of monthly data of the average evapotranspiration over the Tibetan Plateau during 1981–2020.

3.2.3. Mann–Kendall Trend Test

The Mann–Kendall test is often used to test hydrology, climate change, and trend characteristics [27–29]. It is more effective to study the changing trend of hydrometeorological time series than other functions [30]; therefore, the Mann–Kendall trend test method was used to analyze the changing trend of the actual evapotranspiration of the three modal time series (Figure 7). For further analysis and testing, the interannual step change test of 40 years of evapotranspiration was analyzed to obtain whether there was a step change in the time series and to test the step change point to enhance the reliability of the step change result.

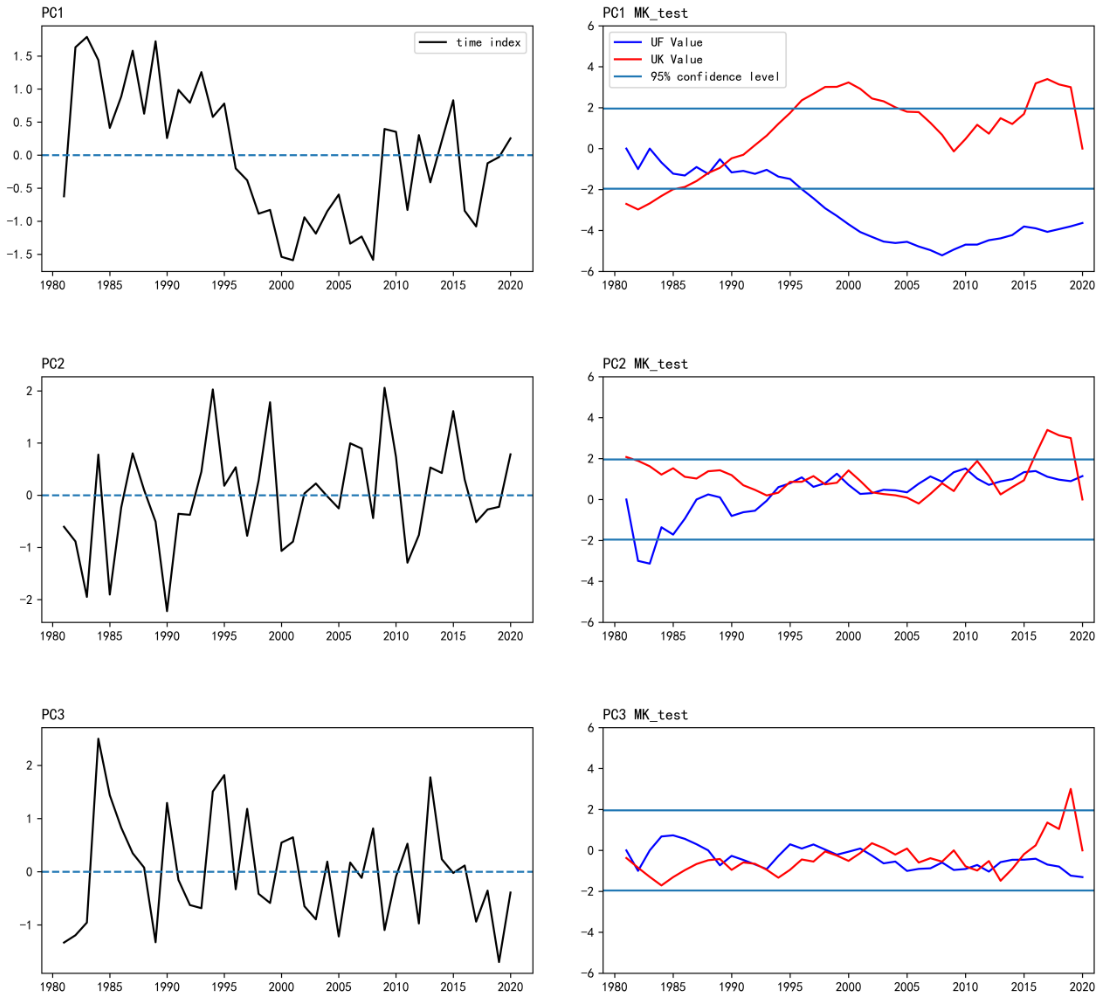

Figure 7. The Mann–Kendall statistical curve of the first (PC1), second (PC2), and third (PC3) modes of the EOF analysis of the average evapotranspiration over the Tibetan Plateau during 1981–2020.

The Mann–Kendall trend test was critical at the 95% confidence level, with a significant value of 1.96. On the premise that the positive sequence (UF) exceeds the critical significance line (95% confidence level), if there is only one intersection point between the positive sequence and the reverse sequence (UK) and it falls within the critical line, then this point is a step change point and in the Mann–Kendall trend. The advantage of the test method is that it can obtain the specific time period when the significant step change occurs [31].

The step change time and region can be further clarified by analyzing the positive sequence UF statistic and the reverse sequence UK statistic. When the two curves of the UF statistic and the UK statistic have an intersection, and the intersection is between the 95% confidence level of the critical straight line, it is the start of the step change. The test results show that the time series of the first mode, the positive series UF, continued to rise from 1980 to 2000, began to decline in the early 21st century, and exceeded the critical significance line around 1996. The positive sequence UF has two intersections, with the reverse sequence around 1988, and falls within the critical line, indicating that there is a step change in evapotranspiration, and the year of step change is 1989. From the time series of the second mode, it can be seen that from the early 1980s, it showed a downward trend, rising in 1994, declining again at the beginning of the 21st century, and then gradually rising in 2006, from the intersection of the positive series UF and the reverse series UK. The step change phenomenon of evapotranspiration can be seen, and the years of step change are 1998, 2002, 2011, 2016, and 2020, respectively. From the trend line of the third mode time series Mann–Kendall test, it can clearly be seen that after 1980, it was in a gradual upward trend, and it increased significantly in 2013. From the intersection of the positive sequence UF and the reverse sequence UK, it can be seen that in the third mode, the step change phenomenon of state occurred in 1989, 2002, 2011, and 2015.

In summary, it can be concluded that the step change years of the time series of the three modes of actual evapotranspiration in the Qinghai–Tibet Plateau calculated by EOF are consistent, and the step change years are 1989, 2002, 2011, and 2015. The overall Mann–Kendall value showed a significant upward trend, indicating that the land water content in the Qinghai–Tibet Plateau was good in the past 40 years, and the evapotranspiration increased significantly.

4. Conclusions

With the continuous enrichment of observational data and the rapid development of numerical models, the research on the effect of the plateau land–atmosphere interaction on the prediction of the East Asian monsoon and regional climate has gradually deepened.

The physical mechanism linking the land–atmosphere interaction of the plateau with the regional climate has been partially answered. This paper reviews the previous research results in related fields and focuses on summarizing the research results of the past four decades. The main research conclusions are as follows:

(1) The evapotranspiration in the southeastern part of the Qinghai–Tibet Plateau is strong and gradually decreases from southeast to northwest. The evapotranspiration had an obvious jump around 1995. Before 1995, evapotranspiration was a negative anomaly in most years, and then turned into a persistent positive anomaly, with obvious interdecadal variations.

(2) There are three spatial modal distributions of evapotranspiration in the Qinghai–Tibet Plateau, which are mainly characterized by a significant and consistent change centered on the Tibet region, an east–west reverse change, and a three-pole “negative-positive-negative” east–west direction type of spatial distribution.

(3) According to the research of Ji Di [32] and Han et al. [33], the temperature of the Qinghai–Tibet Plateau has increased significantly in recent decades, with a temperature increase rate of 0.44 °C/10a. During the past 30 years from 1980 to 2013, the annual precipitation existing in the fluctuation period of 5a and 11a is consistent with the abrupt period and interdecadal variation; the distribution of precipitation increases gradually from northwest to southeast, and the trend of warming and humidification is obvious.

The Qinghai–Tibet Plateau is located in the hinterland and has a special geographical environment. Therefore, it is of great significance to conduct in-depth research on the evapotranspiration process. Moreover, evapotranspiration has an important influence on land surface processes and plays an important role in the region and even the surrounding climate. However, there are still few studies on the temporal and spatial changes of evapotranspiration in the Qinghai–Tibet Plateau, which will restrict the research on land–atmosphere interactions in the region. In this paper, the use of EOF decomposition and power spectrum methods is only a preliminary data statistical study. In the future, discussions should be carried out on the physical mechanism causing the spatiotemporal variations of evapotranspiration, and in the next step, further research can be carried out based on this.

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Data Availability Statement: The data on which the study is based were accessed from a repository and are available for downloading through the following link (https://cds.climate.copernicus.eu/) (accessed on 5 August 2022).

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